6. Dermal Exposure Assessment

6.1 Introduction

Uptake of chemicals through the skin could be significant for some of the contaminants listed under the Air Toxics "Hot Spots" Act. However, it should be noted that dermal absorption of chemicals that are originally airborne is a relatively minor pathway of exposure compared to other exposure pathways. Three different dermal exposure pathways are possible:

a. Uptake of chemicals which have settled onto surfaces, either as particles, droplets, or molecules adsorbed onto a surface (leaves, soil, furniture, etc.).

b. Direct uptake of chemicals from air, either as vapors or from airborne particles or droplets adhering to the skin.

c. Absorption of chemicals from water, after the chemicals have settled into or been absorbed by a body of water. This could involve transport from water-borne particles to skin or direct absorption of molecules dissolved in the aqueous phase by skin.

Dermal absorption will generally provide less exposure to airborne toxicants than inhalation exposure or eating or drinking substances that have been contaminated by airborne chemicals. The risk from dermal exposure in the environmental setting from airborne toxicants will be a small fraction of the risk from inhalation exposure or exposure via ingestion of contaminated crops, soil, breast milk and so on. The significance of each of the above exposure pathways varies by type of chemical, but pathway ***a***, uptake of chemicals from surfaces (in particles), is most relevant. This route applies to semivolatile organic chemicals like dioxins and PCBs, and some metals like lead. Competition between evaporation from the skin and dermal absorption results in a distribution of the chemicals between air, dust particle, and skin phases which depends on volatility, relative solubilities in the phases, temperature, and other factors.

Direct uptake of vapors across the skin, route ***b***, would be most important for volatile chemicals like perchloroethylene, which would remain mostly in the vapor phase. While it is known that dermal uptake is important at high concentrations in the air such as might occur in a workplace, inhalation is a much more important exposure route for volatile compounds in the general population. The other aspect of the air exposure route, direct adherence of airborne particles to skin, is not well documented. In general, contact with particles after they have settled onto surfaces can be expected to predominate. For this document, dermal exposures to particles will be estimated from the particle loads on surfaces and, for soils, an assumed mixing depth of 1 cm.

Exposure route ***c***, dermal uptake from water, is potentially relevant for low-volatility organic chemicals like PCBs or dioxins. However, direct dermal uptake of chemicals in water is minor compared to other routes of exposure for airborne chemicals.

6.2 Factors Providing Significant Variation in Dermal Uptake

As discussed above, dermal absorption varies by exposure pathway and with the properties of the chemical. Other major factors which influence dermal absorption include the anatomical region exposed (Maibach et al., 1971; Wester and Maibach, 1985), the amount of skin exposed, soil or particle type and size, amount of soil adhering to skin (Duff and Kissel, 1996), type of surface contacted, chemical concentration (Nomeir et al., 1992), duration of exposure, ambient temperature and humidity (Chang and Riviere, 1991), and activities which limit exposure (e.g., washing the skin).

In many cases, the inherent variability in the exposure factors can be estimated, such as in total skin surface area of children and adults, or the variability in size of exposed body parts. In some cases, the actual variation is unknown, such as in the average time children of different ages spend in contact with soil. However, reasonable estimates can be made which should encompass the expected range of exposure frequencies and durations. In other cases, the factor involved may be well known but the net effect on dermal absorption of chemicals may not be readily described or quantified. For example, dermal absorption varies with skin temperature and blood flow, which tends to vary with ambient temperature and physical activity. However, the magnitude of this effect is insufficiently documented to support distribution modeling.

This discussion of the variability in dermal exposure estimates is limited to what can be reasonably quantified or estimated at this time, with more attention to the largest exposure routes and activities. Data are very limited for many variates that could be included in a model. The impact of these variates (e.g., ambient temperature, skin moisture content) is presently unquantifiable.

For the Air Toxics "Hot Spots" program, dermal exposure to chemicals in soil is estimated using the following equation currently in the CAPCOA guidelines (CAPCOA, 1993). We are recommending continued use of this equation:

$$\text{Dermal Dose in mg/kg-day} = (\text{Csoil} \times \text{SA} \times \text{SL} \times f \times \text{ABS}) / (\text{ABW} \times 1 \times 10^{9}) \quad \text{(Eq. 6-1)}$$

where:

Csoil =	Concentration of chemical in soil at specific receptor location (μg/kg soil)
SA =	Surface area of exposed skin (cm^2)
SL =	Soil loading on skin (mg/cm^2)
ABS =	Absorption fraction
ABW =	Average body weight (kg)
1×10^9 =	Conversion factors for chemical and soil (μg to mg, mg to kg)
f =	frequency of exposure, days/365 days

The term Csoil, concentration of the contaminant in soil, is derived in the Air Toxics "Hot Spots" program using air dispersion and deposition modeling. The concentration is a

function of the deposition, accumulation period, chemical-specific soil half-life, mixing depth, and soil bulk density. The formula used is:

$$Csoil = [GLC\ (Dep\text{-}rate)\ (86{,}400)\ (X)]\ /\ [Ks\ (SD)\ (BD)\ (Tt)] \quad \text{(Eq. 6-2)}$$

where:
- Csoil = average soil concentration at a specific receptor location over the evaluation period (μg/kg)
- GLC = ground level concentration from the air dispersion modeling (μg/m^3)
- Dep-rate = vertical rate of deposition (m/sec) (see Chapter 2 for values)
- 86,400 = seconds per day conversion factor
- X = integral function accounting for soil half-life
- Ks = soil elimination time constant = $0.693/T_{1/2}$
- SD = soil mixing depth = 1 cm for dermal scenario
- BD = bulk density of soil = 1333 kg/m^3
- Tt = total averaging time = 70 years = 25,550 days

The integral function, X is as follows:

$$X = [\{Exp\ (-Ks \times Tf) - Exp\ (-Ks \times To)\} / Ks] + Tt \quad \text{(Eq. 6-3)}$$

where:
- EXP = Exponent base e = 2.72
- Ks = soil elimination constant = 0.693/ T1/2
- T1/2 = chemical-specific soil half-life
- Tf = end of exposure duration (days); 25,500 for a 70-year exposure
- T_0 = beginning of exposure duration (days) = 0 days
- Tt = total days of exposure period = Tf - T_0 (days)

Chemical-specific soil half-lives are presented in Appendix G. Tf = 25,500 days for a 70-year exposure or less for less-than-lifetime exposures.

The assumptions in the soil concentration algorithm include the uniform mixing of pollutants in the soil, and a constant concentration over the duration of the exposure. For the dermal exposure pathway and for ingestion of soil, the soil mixing depth is assumed to be 1 cm. The bulk density of soils is similar over a wide variety of soil types.

6.3 Exposure Factors and Studies Evaluated

6.3.1 Chemical-specific Factors

Skin permeability is related to the solubility or strength of binding of the chemical in the delivery matrix (soil or other particles) versus the receptor matrix, the skin's stratum corneum. This dermal layer, which is the major skin permeability barrier, is essentially multiple lipophilic and hydrophilic layers comprised of flattened, dead, epidermal cells. The greatest rate of skin permeation occurs with small moderately lipophilic organic chemicals. However, such chemicals may not have the greatest total uptake, because they may evaporate off the skin. The

highest penetration thus is expected from larger, moderately lipophilic chemicals with negligible vapor pressures. Organic chemicals which dissociate in solution or metal salts are more soluble in the aqueous phase of stratum corneum and insoluble in the lipid phase, and thus penetrate skin poorly.

These principles of skin absorption rates are documented in U.S. EPA (1992), as summarized in Appendix F.

Cal/EPA has attempted to define appropriate values to use for dermal absorption estimates for occupational exposure to pesticides (Department of Pesticide Regulation (DPR) 1993) and for potential exposure to chemicals at hazardous waste sites (Department of Toxic Substances Control (DTSC) 1993, 1994). The guidelines in DPR (1993) and DTSC (1994) stress use of human data, where available, but do not provide clear guidance on inferred data distributions. They suggest use of point estimates for health-protective default values. The CalTOX computer program (DTSC, 1993), by contrast, provides a mechanism for screening health risks at hazardous waste sites. CalTOX incorporates explicit assumptions for distributions of all exposure parameters but is focused on dermal uptake of contaminants poured directly onto soil, and at concentrations higher than one would anticipate from airborne deposition.

Chemical-specific dermal absorption is discussed in Appendix F.

6.3.2 Concentration and Ttemperature Dependence of Uptake

The percent of an applied dose that is absorbed across the skin has often been observed to be inversely proportional to the concentration applied (Chang and Riviere, 1991; Wester and Maibach, 1985; Wester et al., 1993b). Total dermal uptake does not always decrease with increasing concentration on skin (Nomeir et al., 1992). Chang and Riviere (1991) also demonstrated the effect of variations in the air temperature and humidity. In vivo the absorption of moderately polar substances has also been related to stimulating blood perfusion and opening pores (Loomis, 1980), although it should be noted that hydration will slow the penetration of highly lipophilic chemicals (Feldmann and Maibach, 1965).

6.3.3 Skin Area Factors

The U.S. EPA guidelines on dermal uptake parameters for risk assessment (1992, 1995, 1997) for chemicals in soil provide for surface area and soil contact factors to vary by exposure scenario. The default values for soil contact include, for adults, a skin area of 5,000 to 5,800 cm^2, a soil to skin adherence rate of 0.2 to 1.0 mg/cm^2-event, and an exposure frequency of 40-350 events/year. The exposed surface area estimate assumes 25% of the body is exposed, roughly corresponding to wearing shoes, shorts, and a short-sleeved shirt. The event frequency range of 40 to 350/year is based on judgments (no actual data) regarding behavior involving soil contact such as gardening.

A considerable amount of data is available on the permeability of different skin areas for uptake of environmentally relevant chemicals (Maibach et al., 1971; Wester and Maibach, 1985; Finley et al., 1994a). In general, hands are least permeable, and face and neck are most

permeable. Most exposure estimates have utilized a single value for presumed dermal uptake rate or percent, without distinguishing between the surface areas that might be involved under different scenarios.

6.3.4 Soil Adherence Factors

A review of the literature by Finley et al. (1994b) suggests a probability distribution for soil adherence to skin which is independent of age, sex, soil type, or soil particle size. Data from several different studies were used to simulate probability distribution functions (PDFs) with a bootstrapping Monte Carlo analysis for both adults and children. Finley et al. combined several studies for a single probability distribution function. This PDF is lognormally distributed with an arithmetic mean of 0.52 ± 0.9 mg soil/cm^2 of skin; the 50 and 95th percentiles are 0.25 and 1.7 mg soil/cm^2 of skin.

Dermal soil loading was estimated in the study of Kissel et al. (1996) by weighing the soil particles washed off the skin and collected by filtration, after various activities. Skin surfaces evaluated included hand, forearms, lower legs, face, and feet. Observed hand loadings varied over five orders of magnitude, from 0.001 to 100 mg/cm^2, mostly dependent on the type of activity. Hand loadings within the current regulatory default estimates, 0.2 to 1.0 mg/cm^2, were produced by activities resulting in direct and vigorous contact with soil such as rugby and farming. Several other outdoor activities resulted in less soil loading on hands. The worst case was represented by children playing in mud on a lakeshore, who accumulated 10 mg/cm^2 or more on hands, arms, legs, and feet, for a total body load of soil far in excess of the default values. The general conclusion of Kissel et al. is that current default soil loading estimates will greatly overestimate exposure to chemicals in soil for activities which do not result in direct soil contact; typical "background" geometric mean soil loading was on the order of about 0.01 mg/cm^2. It should be noted that this technique measures only net soil loading, ignoring any soil/skin chemical transfer which might occur from short-term residence of particles on skin during the activity.

6.3.5 Soil Layer Thickness

Transfer of a chemical from soil particles on skin to the skin surface is limited by the chemical's diffusion rate (McKone, 1990). Diffusion through the soil phase, through the air, and through soil moisture are all possible. Fugacity-based interphase transport models were constructed by McKone to describe the rate of each of these processes for chemicals in soil particles and to predict the dermal uptake rates. It was shown that predicted dermal uptake of chemicals from soil depends on the Henry's constant (vapor pressure/solubility in water), the octanol/water partition coefficient of a chemical, and the soil thickness on skin. If the Henry's constant is very high, chemicals will be lost from soil particles (or the skin surface) quite rapidly, so net dermal uptake of chemicals added to soil will be low. If the Henry's constant is very low, diffusion through the soil particle layer will be too slow to allow much dermal uptake unless the soil particles are very small. A high octanol/water partition coefficient is associated with tight binding to soil and low water solubility; these properties also limit the ability of a chemical to diffuse through the mixed lipid/water phases of the stratum corneum. The McKone model was used to predict that high soil loadings would not yield high dermal absorption for chemicals like

2,3,7,8-TCDD, because of transport limitations. An uptake of 0.5% of the soil content of TCDD was predicted with the model at a soil loading of 20 mg/cm^2 on skin, compared to a measured value of 1% in rats at this soil loading.

6.3.6 Clothing Penetration Values

Studies on penetration of pesticide residues on crops through clothing of the workers picking the crops provide relevant data on potential exposure to environmental chemicals on surfaces under a variety of conditions. Brodberg and Sanborn (1995) surveyed studies conducted by or submitted to the Department of Pesticide Regulation for evaluation of agricultural worker exposure to pesticides. Transfer of pesticides through clothing was estimated by measuring the difference in amounts of pesticides recoverable on an inner layer of clothing or an absorbent patch, compared to the total amount recovered on both inner and outer clothing or patches. The data varied from 10 to 34% with no penetration trends that could be ascribed to the crop, the type of activity (ground, tree, or bush harvest), or the chemical. As observed by Brodberg and Sanborn (1995), the low vapor pressure of these chemicals makes it unlikely that the chemicals moved through the clothes in the vapor phase. Rather, penetration of clothes by being carried on dust particles is likely, which could explain the lack of penetration trends noted above.

For two pesticides on peaches, there was an apparent difference in penetration of pesticides through the clothing on different parts of the body. The low penetration on hands (8 to 9%) is likely to be due to the low permeability of the nylon gloves worn, compared to the cotton/polyester clothing on the rest of the body. The highest penetration rates, for upper arms (42 to 48%) and shoulders (30 to 37%), is ascribed by Brodberg and Sanborn to the type of activity involved in reaching up for peaches, involving extra contact with both clothing and foliage.

Brodberg and Sanborn (1995) recommend a default value for penetration through clothing of 25%, to be used in the absence of more specific data. The current DPR Worker Health and Safety Branch default value is 10% clothing penetration (personal communication, 1996).

6.3.7 Behavioral Factors

People's activities are the major determinant of their exposure to soil and dust (Wiley et al., 1991a,b; U.S. EPA, 1995; Kissel et al., 1996), but frequencies and durations of soil exposures are not well characterized. The Air Resources Board's activity pattern studies in adults and children (Wiley et al., 1991a,b) reveal patterns of individual activities but do not provide direct information on contact with soils. Estimates of activities which would result in soil contact have previously been generated on the basis of what seemed to be "reasonable" scenarios. To incorporate the uncertainty in estimates of soil exposure, it is necessary to use the scenario concept, e.g., to estimate exposure for a preschool child who plays outdoors several hours each day, as well as for an adult who rarely engages in outdoor activities. This provides information on reasonable range of exposure.

6.4 Dermal Uptake Estimation Equations

6.4.1 U.S. EPA Exposure Estimates (1992, 1995)

The U.S. EPA (1992) suggested using the following equation for estimating dermal exposure to chemicals from soil:

$$ADD = \frac{DA_{event} \times EV \times ED \times EF \times SA}{BW \times AT} \qquad \text{(Eq. 6-4)}$$

where:

ADD =	average daily dose (mg/kg-day)
DA_{event} =	absorbed dose per event (mg/cm^2-event)
EV =	event frequency (events/day)
EF =	event frequency (days/yr)
ED =	exposure duration (years)
SA =	skin surface area available for contact (cm^2)
BW =	body weight (kg)
AT =	averaging time (days); for noncarcinogenic effects, AT = ED, for carcinogenic effects, AT = 70 years or 25,550 days

The absorbed dose per event, DA_{event}, uses a percent absorption calculation which considers chemical-specific absorption estimates and the soil type and skin adherence factor.

For estimating children's doses over a range of ages, the U.S. EPA Dermal Exposure Assessment (1992) suggests a summation approach to represent changes in surface area and body weight as a person grows. Assuming all other exposure factors remain constant over time, Equation 6-4 for uptake from soil would be modified to:

$$ADD = \frac{DA_{event} \times EF}{AT} \times \sum_{i=m}^{n} \frac{ED_i \times SA_i}{BW_i} \qquad \text{(Eq. 6-5)}$$

where $\sum$ represents a summation of terms, and *m* and *n* represent the age range of interest.

6.4.2 Cal/EPA Department of Pesticide Regulation Guidance for the Preparation of Human Pesticide Exposure Assessment Documents (1993)

The DPR dermal absorption estimate procedure uses a default uptake value of 100% unless a pesticide registrant chooses to collect specific data (DPR, 1993). DPR has recently proposed 50% absorption as a default on the basis of a survey of previous pesticide absorption studies. Experimental absorption values are calculated from in vivo data as follows:

$$\text{Percent dermal absorption} = \frac{\text{Applied dose - Unabsorbed dose}}{\text{Applied dose}} \times 100 \quad \text{(Eq. 6-6)}$$

or the absorbed portion may be calculated from the sum of all residues found in excreta, expired air, blood, carcass, and skin at the site of application (after washing), or estimated from the asymptotic plot of all (radioactively-labelled) residues excreted in feces, urine, and air. Absorption rate in an animal experiment in vivo is assumed to be applicable to humans, unless it can be corrected with the ratio of in vitro uptake in animal vs. human skin.

6.4.3 CalTOX (1993)

The CalTOX computer program (DTSC, 1993) incorporates variable parameters in each exposure pathway to estimate multimedia uptake of a chemical by all exposure routes, with the uncertainty assumptions explicitly presented. For the dermal uptake route, a soil/skin transport model is included (McKone and Howd, 1992). The basic uptake model is:

$$ADD = AR_s \times SA_b \times 0.3 \times 15 \times EF_{sl}/365 \times C_g \quad \text{(Eq.6-7)}$$

where:

- ADD = average daily dose in mg/kg-day, for one exposure event/day
- AR_s = ratio of the absorbed dose to the soil concentration, e.g., uptake per unit area of skin per unit concentration in soil in mg/cm^2 per mg/cm^3
- SA_b = body surface area per kg, in m^2/kg
- 0.3 = fraction of total body exposed to soil, default value; coefficient of variation (CV) assumed = 0.04
- 15 = conversion factor for soil density, in kg/cm-m^2, based on a soil bulk density of 1500 kg/m^3
- $EF_{sl}/365$ = exposure frequency in days/year, divided by the days in a year; mean assumed = 137, CV = 0.6
- C_g = chemical concentration in soil (mg chemical/kg soil).

The absorbed dose for each event is calculated with the following equation:

$$AR_s = T_s \times \left\{ 1 - \exp\left[\frac{-K^s_p \times ET_{sl}}{T_s} \right] \right\} \qquad \text{(Eq. 6-8)}$$

where:

AR_s = skin uptake as defined above
T_s = thickness of soil layer on skin, in cm
$-K^s_p$ = permeability factor for chemical movement from soil into skin, in cm/hour
ET_{sl} = soil exposure time, in hours/day.

The thickness of the soil layer on skin, T_s, depends on the soil loading factor, which was assumed to be 0.5 mg/cm^2, with CV = 0.4. The permeability factor, K^s_p, is derived from permeability values, K_p, from water, with a correction for decreased skin hydration. ET_{sl} is set equal to half the total exposure time at home.

6.4.4 *Frequency of Exposure to Soil*

Soil exposure frequency is the final parameter of significance in these exposure estimates. Existing survey data are not reliable because individual activity patterns have not been monitored long enough to document differences in individual behavior. A range of assumptions of soil exposure frequencies has been used in different contexts. The following summary (Table 6.1) is derived from the U.S. EPA Exposure Factors Handbook (1995):

Table 6.1 Assumptions of frequency of exposure to soil

Range, days/year	Population	Reference
350	all	U.S. EPA, 1989
247-365	all	U.S. EPA, 1984
180	all	Paustenbach et al., 1986
130	children < 2-5	Hawley, 1985
130	older children	Hawley, 1985
45	adults	Hawley, 1985

The various estimates may include different exposure assumptions -- i.e., colder vs. warmer climates. The U.S. EPA has considered Hawley's adult exposure frequency to be applicable to adults who garden or otherwise work outside one to two days per week during the warmer months. However, to maintain consistency with their earlier estimates, the U.S. EPA also continued the use of 350 days per year as an upper estimate of the frequency of soil exposures for adults.

6.5 Recommendations

The dermal exposure pathway generally contributes little to the risk of airborne substances under the typical facility operation and exposure scenarios in the Air Toxics "Hot Spots" program. We are recommending a simple point estimate approach to assessing dermal

exposure. Under some circumstances, a more complex approach may be warranted. The analyst may then want to consult the CalTOX program and the U.S. EPA document *Dermal Exposure Assessment: Principles and Applications* (1992). We recommend estimating the dermally absorbed doses from soil using Eq. 6-1. For the point estimate approach, OEHHA recommends using the standard CERCLA default values for the variables in equation 6-1 (U.S. EPA, 1989, 1991). These are described in Table 6.2 below. For a 30- or 70-year exposure scenario, we recommend the values under "TWA 0-70" in Table 6.2. For a 9-year scenario, we recommend the values for children 1-6 years in Table 6.2. The suggestions below constitute a proposed "standard" evaluation useful in a Tier 1 (point estimate) risk assessment. Other estimation methods which are based on a specific exposure scenario may be presented in a Tier 2 risk assessment.

Table 6.2 Recommended point estimate defaults for dermal exposure.

	Children (1-6 yrs)	Adults (> 6 yrs)	TWA 0-70 years
surface area exposed (cm^2)	2000	average = 5000 high-end = 5800	average = 4700 high-end = 5500
soil loading (mg/cm^2)	average = 0.2 high-end = 1.0	average = 0.2 high-end = 1.0	average = 0.2 high-end = 1.0
Exposure frequency (d/yr)	350	average = 100 high-end = 350	average = 121 high-end = 350

The use of point estimates is proposed for the other factors in Equation 6-1,

Csoil = concentration of chemical in soil (mg/kg)
ABS = fractional dermal absorption of the chemical
AT = averaging time (days); for noncancer effects, AT = the sum of exposure terms, T_i (converted to days); for cancer, AT = 25,550 days (70 years).

A point estimate of concentration generated from the air dispersion and deposition modeling, Csoil, is used to calculate dose (see Equations 6-2 and 6-3). The point estimates representing concentrations at the point of maximum impact, maximum exposed individual resident and maximum exposed worker are used in the Air Toxics "Hot Spots" program. However, the concentration of the chemical in soil could be modeled for other receptor points of interest, and it could be appropriate to estimate risks at various mean concentrations. The algorithm for calculating soil concentration incorporates soil half-life.

The fraction of the applied chemical that is dermally absorbed, ABS, depends on both chemical-specific factors and scenario-dependent factors. As indicated in the discussions in section 6.3 above and in Appendix F, these can result in orders-of-magnitude differences in dermal uptake under different conditions. Data are inadequate to describe potential changes in fractional dermal absorption with changing scenario. The point estimate values to be used for dermal absorption estimates are discussed in Appendix F.

The averaging time (AT) depends on scenario and effect (cancer vs. non-cancer). In a cancer risk assessment the averaging time is 70 years, while the exposure duration may be 9, 30 or 70 years (see Section 11). Dermal doses estimated by these methods are equivalent to an internal dose by U.S. EPA definition (U.S. EPA, 1992).

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